

A Testbed for Mars Precision Landing Experiments by Emulating Spacecraft Dynamics on a Model Helicopter

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Abstract

We propose the use of a model helicopter to emulate the landing dynamics of a spacecraft. Our controller accepts thruster inputs (like those on a spacecraft) and converts them into appropriate helicopter stick controls such that the resulting trajectory of the helicopter is close to the trajectory that would have been achieved by simply providing the same thruster inputs to a spacecraft. The approach relies on a simplified model of the spacecraft and helicopter dynamics. Initial results in simulation indicate that the approach is feasible, with tracking accuracies on the order of 5 m.

1 Introduction

Landing sites for past missions to Mars have, for the most part, been located in relatively benign terrain. The need to avoid extremely rocky or sloped areas was due to the inaccuracy of the guidance system and due to the inability of the landing system to accommodate such features [1]. A landing accuracy of better than 100 km is difficult to achieve and landing systems employed by vehicles such as Pathfinder were unable to accommodate large hazards or significant surface roughness [2]. The scientific missions for future Mars exploration require increasing accuracy in the specification of the landing site. Landing in small craters or ancient lake beds considered to be prime sites for potential exobiology requires precision landing capabilities. Landing safely in close proximity to hazardous terrain necessitates improved landing vehicle accuracy and robustness.

The next generation of Martian landers (2007 and beyond) will employ precision soft-landing capabilities [3] based on vision. These algorithms will have to be tested with extensive descent imagery in Mars-analog terrain on Earth. To enable this, we propose a novel technique for testing spacecraft landing algorithms during the terminal landing phase. Our technique consists of using an autonomous unmanned model helicopter which emulates

the dynamics of a spacecraft (e.g. a Mars lander). A helicopter is a highly maneuverable and versatile platform for several reasons: it can take off and land vertically, hover in place, perform longitudinal and lateral flight thus making it an ideal platform for emulating a spacecraft.

In our approach a control emulation layer is wrapped around the helicopter controller. The resulting system is able to accept thruster inputs and is able to follow trajectories like a spacecraft. We believe such a testbed would be valuable to validate the trajectory following and precise landing algorithms being developed for future Martian landers.

To simplify matters, we consider the planar landing problem where the craft has three degrees of freedom. Of these, we focus on height and roll. We present simulation results showing that our system is able to track the trajectory of a spacecraft executing a simple landing maneuver. The concept is attractive since one could test a variety of landing algorithms on a cheap platform before actually implementing them on a Mars lander.

The idea of precise landing on Mars is relatively new. Prior research on controlled atmospheric maneuvering of a vehicle in the Martian atmosphere [4, 5], has not focused on the terminal stage of landing. [4] discusses drag-based predictive tracking for landing with a terminal error of 2.9 km on the ground. [6] are developing a system based on scanning laser data for safe and precise landing on Mars. They use a rocket sled for testing their algorithms. Although several simulations have been performed by [4, 6] the lack of a proper testbed has prevented validation.

The task of performing controlled descent during the landing phase of a spacecraft is difficult since one has to take into account 1. the atmospheric uncertainty, 2. variation in gravity, 3. the rotation of the planet, and 4. ground-effect on the dynamics of the spacecraft when near the ground. In the present work we focus on the terminal phase of landing with the assumption that the first three

are insignificant at low altitudes. As far as we know no one has tried to perform precise landing trajectories by simulating them on another dynamical model though the idea of emulating the dynamics of one system on another is not new and has been used in robotics with successful results in teleoperation [7]. It may be noted that we have several years of experience in the autonomous control of robot helicopters [8], including vision-based landing [9], however in contrast to our previous work which was model-free, here we consider a controller for a helicopter based on an explicit dynamic model.

2 Problem Formulation

We formulate the problem as follows:

Problem: *Given a model of a spacecraft with thruster inputs for control, and given a desired landing trajectory, what are the corresponding stick inputs for a model helicopter to track the given landing trajectory?*

The generalization of this problem is to find stick inputs for a model helicopter for the entire range of a family of trajectories. Although such problems have been considered for general cases [10], to our knowledge, this is the first time that such a formalization is being applied to a combination of spacecraft and helicopter.

Typically landing trajectories consist of controlling the position, velocity $x, y, z, \dot{x}, \dot{y}, \dot{z}$ and the roll, pitch and yaw of the craft. In this paper we consider a constrained (planar) version of the above problem with three degrees of freedom (vertical and horizontal position, and roll) and two control inputs (vertical thrusters).

As a simple example of the desired trajectory, we consider a cubic polynomial trajectory for spacecraft landing where the altitude z_s varies with time t as follows:

$$z_s(t) = a_0 + a_1 \cdot t + a_2 \cdot t^2 + a_3 \cdot t^3 \quad (1)$$

with the following conditions

$$z_s(0) = z_{so} \quad z_s(t_f) = z_{sf} \quad \dot{z}_s(0) = 0 \quad \dot{z}_s(t_f) = 0$$

where t_f is the final time. Similarly for spacecraft roll ϕ_s consider a linear time varying trajectory given by

$$\begin{aligned} \phi_s(t) &= b_0 + b_1(t) \\ \phi_s(0) &= \phi_{so} \quad \phi_s(t_f) = 0 \end{aligned} \quad (2)$$

2.1 Assumptions

Since we are interested in the 'terminal' phase of the landing problem, we make several simplifying assumptions:

- Change in spacecraft mass due to thruster firings is small.
- Rotation and curvature of the planet is negligible.

Table 1: *Nomenclature: The subscript s refers to the spacecraft, h refers to the helicopter.*

ϕ_s, θ_s, ψ_s	roll,pitch,yaw angles in the body frame
p_s, q_s, r_s	roll,pitch,yaw rates in the body frame
u_s, v_s, w_s	velocities in the body frame
F_{s1}, F_{s2}	thruster inputs
X_s, Y_s, Z_s	Forces in the x,y,z directions in the body frame
L_s, M_s, N_s	Moments on the spacecraft in the body frame
x_s, y_s, z_s	translational positions in inertial frame
z_{so}, z_{sf}	Initial and final position in the inertial frame
ϕ_{so}	Initial roll
M_s	Mass of the spacecraft
$I_{xxs}, I_{yys}, I_{zzs}$	Moments of inertia
α, β	Moment arms for thrusters F_{s1} and F_{s2} respectively
ϕ_h, θ_h, ψ_h	roll,pitch,yaw angles in the body frame
ω_h	angular velocity vector in the body reference frame
V_h	velocity vector in the body reference frame
$\delta_{coll}, \delta_{roll}$	collective and roll cyclic inputs to the helicopter
x_h, y_h, z_h	translational positions in the inertial frame
M_h	Mass of the helicopter
I_h	Rotational inertia matrix of the helicopter
$I_{3 \times 3}$	Identity Matrix

- Centripetal and Coriolis forces are not modeled.
- Both the spacecraft and the helicopter are modeled as rigid bodies.
- The effect of wind and other atmospheric turbulences are not considered.
- The spacecraft is assumed to have two thrusters to control the roll and height.
- The helicopter is controlled via two control inputs: collective and the roll cyclic.

3 Mars Lander-Spacecraft Dynamics

The equations of motion for the spacecraft are modeled as a rigid body with six degrees of freedom in space and are given by the Newton-Euler equations shown below [11].

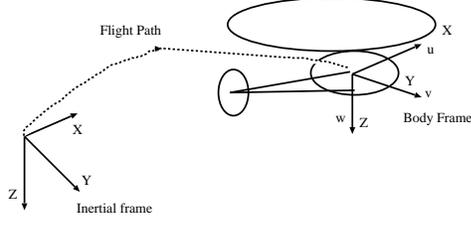


Figure 1: Coordinate frames (The same frame assignment holds for the spacecraft)

$$\begin{aligned}
\dot{u}_s &= v_s r_s - w_s q_s - g \sin \theta + \frac{X_s}{M_s} \\
\dot{v}_s &= w_s p_s - u_s r_s - g \cos \theta_s \sin \phi_s + \frac{Y_s}{M_s} \\
\dot{w}_s &= u_s q_s - v_s p_s - g \cos \theta_s \cos \phi_s + \frac{Z_s}{M_s} \\
\dot{p}_s &= \frac{(I_{yys} - I_{zz1})q_1 r_1 + L_s}{I_{xx1}} \\
\dot{q}_s &= \frac{(I_{zzs} - I_{xxs})p_s r_s + M_s}{I_{yys}} \\
\dot{p}_s &= \frac{(I_{xxs} - I_{yys})q_s p_s + N_s}{I_{zzs}} \\
\dot{\theta}_s &= q_s \cos \phi_s - r_s \sin \phi_s \\
\dot{\phi}_s &= p_s + [q_s \sin \phi_s + r_s \cos \phi_s] \tan \theta_s \\
\dot{\psi}_s &= [q_s \sin \phi_s + r_s \cos \phi_s] \sec \theta_s
\end{aligned} \tag{3}$$

The state variables are $u_s, v_s, w_s, p_s, q_s, r_s$. Two thrusters are used for control actuation. These are modeled as two forces, F_{s1} and F_{s2} . For small perturbations [12] the model can be approximated by

$$\begin{aligned}
\dot{w}_s &= -g \cos \theta_s \cos \phi_s + \frac{Z_s}{M_s} \\
\dot{p}_s &= \frac{L_s}{I_{xxs}} \\
\dot{\phi}_s &= p_s \\
\dot{z}_s &= w_s \cos \phi_s \cos \theta_s
\end{aligned} \tag{4}$$

Since we are considering only roll and height, only those equations are given above. For a particular trajectory, a closed loop controller can be now be written (using the above equations) to perform trajectory control. The inputs to the controller are the force acting on the spacecraft in the vertical direction Z_s and the moment L_s . These are calculated from the two thruster inputs F_{s1} and F_{s2} as follows

$$\begin{aligned}
Z_s &= F_{s1} + F_{s2} \\
L_s &= F_{s1}\alpha + F_{s2}\beta
\end{aligned} \tag{5}$$

3.1 Controller for Landing

A simple P-controller is implemented for tracking the desired height and roll given in Equations 1, 2. The con-

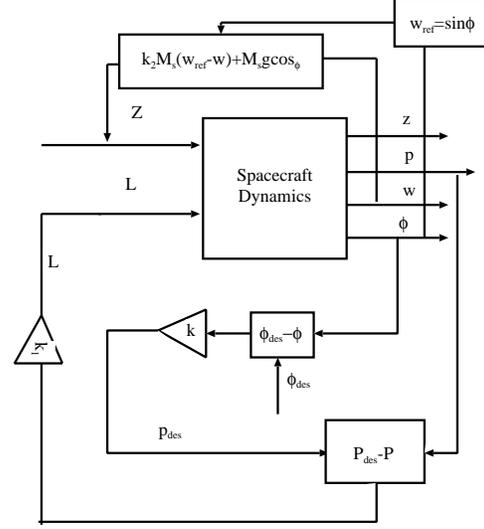


Figure 2: Multi-stage P-controller for the Spacecraft (k, k_1, k_2 are the gains)

troller is shown in greater detail in Figure 2 and the corresponding equations¹ are given by Equation 7

$$\begin{aligned}
Z_s &= K_1 M_s (w_{sref} - w_s) + M_s g \cos \phi_s \\
L_s &= I_{xxs} K_2 (p_{sref} - p_s) \\
p_{sref} &= K_3 (\phi_{sref} - \phi_s)
\end{aligned} \tag{6}$$

3.2 Helicopter Model

The four independent inputs to a helicopter are Γ , the net thrust generated by the main rotor, and $M_{\phi_h}, M_{\theta_h}, M_{\psi_h}$ the net moments acting on the helicopter. These four inputs in a model helicopter are physically controlled by two joysticks on a radio transmitter, each with two degrees of freedom. The left joystick commands throttle with collective pitch (up/down) δ_{coll} and yaw (left/right), and the right joystick commands pitch cyclic (up/down) and roll cyclic (left/right) δ_{roll} . The four values representing the positions of the joysticks are pulse-width modulated (PWM), and sent via radio transmitter to the helicopter.

Our physical helicopter [13] is autonomously controlled, and hence the stick inputs are generated by using a PD controller based on the reference values. Currently no dynamical model of our helicopter exists. We assume that the roll, pitch and yaw of the helicopter are decoupled, and control them independently. This has the disadvantage that the helicopter has a very limited flight regime and cannot be used for emulating the landing trajectories of a spacecraft. In future work, we plan to use the model developed in [14] (described below), and identify it for our helicopter. Note that the gains $K_4 \dots K_{12}$ in Equations 7 depend on accurate system identification. For the

¹The inertial cross terms I_{yz}, I_{zx}, I_{xy} are neglected

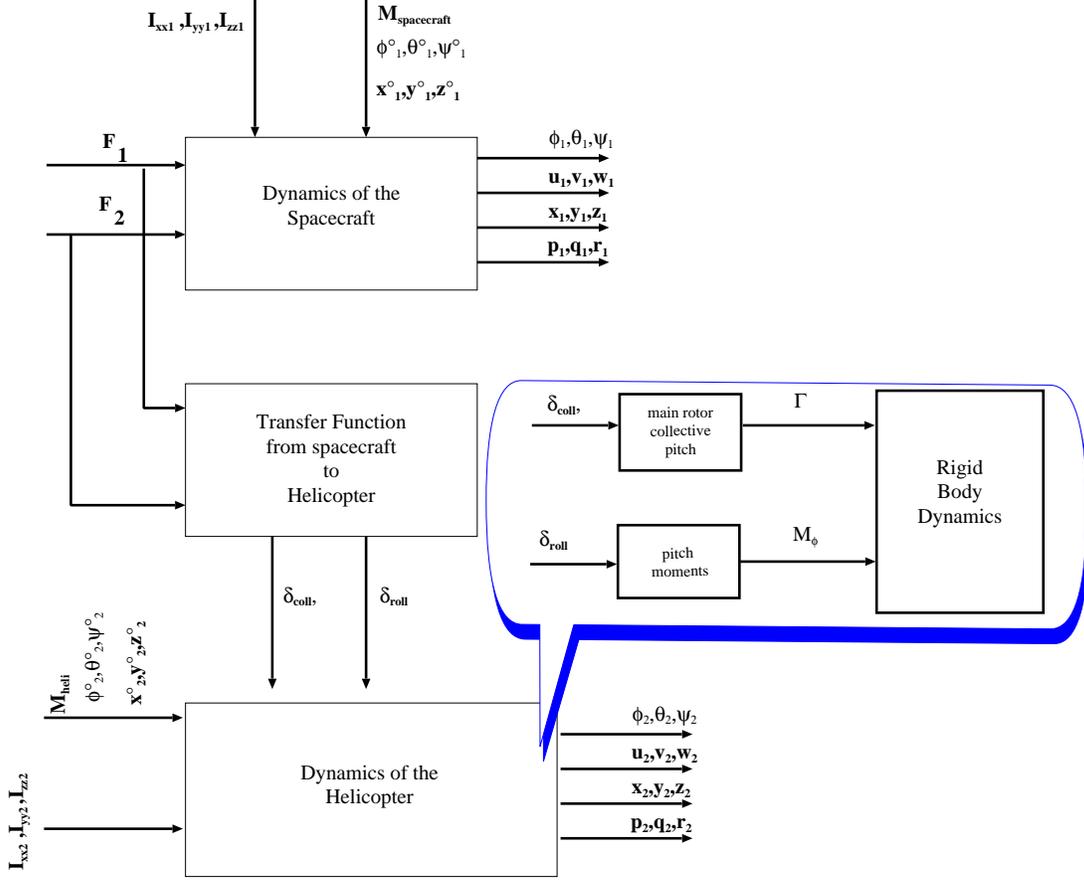


Figure 3: Schematic Representation of the Emulator

results presented in this paper we use the gains from [14], as proof of concept. The model [12] is obtained by considering the helicopter as a rigid body in space and ignoring the effects of the spinning rotor.

$$\begin{pmatrix} M_h I_{3 \times 3} & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} \dot{V}_h \\ \dot{\omega}_h \end{pmatrix} + \begin{pmatrix} \omega_h M_h V_h \\ \omega_h I \omega_h \end{pmatrix} = \begin{pmatrix} f \\ \tau \end{pmatrix}$$

where the external forces and torques acting on the helicopter in the body frame are given by f and τ . The throttle/collective command δ_{coll} controls the thrust to the main rotor as well as the collective pitch (θ_o) of the main rotor blades. The collective pitch [14] and the thrust on the main rotor are given by Equation 7

$$\begin{aligned} \ddot{\theta}_o + K_9 \dot{\theta}_o + K_{10} \theta_o &= K_{11} \delta_{coll} \\ \Gamma &= K_{non-linear} \left(\frac{C^3}{3} \theta_o - \frac{C^2}{2} \right) \end{aligned} \quad (7)$$

where C is a constant which models the atmospheric uncertainties. Extensive modeling of the dynamics of a model helicopter is discussed in [14]. We use those results to perform the simulations reported here. The transfer function for height as a function of collective stick

command is given by

$$\frac{Z_h(s)}{\delta_{coll}(s)} = \frac{K_4 K_5}{(s^2 + K_6 s + K_7)(s^2 + K_8 s + K_9)} \quad (8)$$

Similarly the transfer function for roll as a function of roll cyclic stick command is given by

$$\frac{\phi_h(s)}{\delta_{roll}(s)} = \frac{K_{12}}{s(s + K_{13})} \quad (9)$$

4 Emulator Design

The next step is the design of the emulation layer which takes the forces F_{s1} and F_{s2} as inputs and converts them to roll and collective commands to the helicopter. This “emulator function” is given by:

$$\begin{aligned} \delta_{coll} &= F_{s1} + F_{s2} \\ \delta_{roll} &= \int_0^T \int_0^T (F_{s1} - F_{s2}) dt dt \end{aligned} \quad (10)$$

where T is the total time of flight. For finding the reference values of the roll and collective commands $\delta_{collref}$ and $\delta_{rollref}$, we take the height trajectory as obtained from the spacecraft and simply invert the linear transfer

functions in Equations 8, 9. Notice that even though we are inverting the linear transformation functions in Equations 8, 9, we will not be able to track the specified trajectories because of the coupling between the roll and the collective inputs.

We use a PID controller given by

$$\delta_{coll_{eff}} = K_{coll}(\delta_{collref} - \delta_{coll}) + K_{dcoll}(\dot{\delta}_{collref} - \dot{\delta}_{coll}) + K_{icoll} \int (\delta_{collref} - \delta_{coll}) \quad (11)$$

$$\delta_{roll_{eff}} = K_{roll}(\delta_{rollref} - \delta_{roll}) + K_{droll}(\dot{\delta}_{rollref} - \dot{\delta}_{roll}) + K_{irroll} \int (\delta_{rollref} - \delta_{roll}) \quad (12)$$

based on the reference values $\delta_{collref}$ and $\delta_{rollref}$ and values, which are given by Equation 10. $K_{coll}, K_{dcoll}, K_{icoll}, K_{roll}, K_{droll}, K_{irroll}$ are the PID gains. The $\delta_{coll_{eff}}$ and $\delta_{roll_{eff}}$ are the inputs to the helicopter.

5 Results

For finding the gains we used a trajectory for height given by

$$z_s(t) = -150 + 4.5 \cdot t^2 - 0.3 \cdot t^3 \quad (13)$$

The above equation satisfies the constraints specified in Equation 1 at $t = 10$ seconds. This is a sample trajectory and by no means restricts the class of trajectories which can be given to the controller. For roll we consider a linear time varying trajectory given by

$$\phi_s(t) = \frac{\pi}{10} - \frac{\pi}{100}t \quad (14)$$

Using the height and roll given by Equations 13 and 14 as the reference, the forces F_{s1} and F_{s2} , which are the inputs to the spacecraft, are calculated [section 3.1]. The values $\delta_{collref}$ and $\delta_{rollref}$, which the helicopter requires for tracking the same trajectory [Equations 13, 14] are calculated by inverting the dynamics of the helicopter. [section 3.2].

The quantities calculated using Equation 10 are the values which are inputs to the PID controller [Equations 11, 12]. Since we know the desired trajectory to be followed, the reference values and the inputs, the gains for the controller can be obtained. This PID controller with the specified gains is used in all subsequent trials for tracking other trajectories. For tracking a new trajectory the δ_{coll} and δ_{roll} inputs to the helicopter are calculated using Equation 10. The reference inputs for the controller $\delta_{collref}$ and $\delta_{rollref}$ would change since we are tracking a new trajectory. Let us denote these reference inputs by $\delta_{coll_{newref}}$ and $\delta_{roll_{newref}}$. These are calculated as

$$\delta_{coll_{newref}} = \delta_{collref} + D\ddot{z}_s(t) \quad (15)$$

$$\delta_{roll_{newref}} = \delta_{rollref} + D_1\dot{\phi}_s(t) \quad (16)$$

where D and D_1 are gains which are obtained empirically. The PID controller given by Equations 11 and 12 is used for tracking this new trajectory.

In Figure 4(g) the results of trajectory tracking are given and in Figure 4(h) the result of tracking a given roll is given. This corresponds to the initial run from which the PID gains for the tracking controller given by Equation 11 are determined. The gains so obtained are used in the second trial (with different initial conditions). The height and roll trajectories for the second trial are given by

$$z_s(t) = -75 + 2.25(t^2) - 0.15(t^3) \\ \phi_s(t) = \frac{\pi}{5} - \frac{\pi}{50}t \quad (17)$$

The performance of the controller, for the trajectory given by Equation 17 is shown in Figures 5(g) and (h). As seen from the figures, the spacecraft emulation controller performs quite well and the transfer function although simple, is able to track the required trajectory and the roll with accuracy.

6 Analysis of Simulation Results

Figure 4 was obtained by fitting a cubic polynomial to initial height 150 m and the final height 0 m. The initial and final velocities were both zero. A simple P-controller was used for both height and roll control (the height controller was based on angular velocity, and the roll controller was based on the roll rate) as described in section 3. The spacecraft was considered to have two thrusters on it for controlling roll and height. The forces required for controlling the spacecraft are described in section 3.1. These forces were inputs to the helicopter controller. Roll input was obtained by integrating the difference between the thruster forces twice, whereas the collective input was just the sum of the thruster forces. A PID controller was used for the helicopter. The gains were derived from an initial trial with particular initial conditions. Figure 5 (g),(h) shows the desired values and the tracking values obtained from the helicopter controller.

A second trial used the same controller as the first (gains unchanged) but the initial height was changed to 75m. From Figure 5 it is apparent that the system tracks fairly well. The tracking error which is defined as the difference between the actual trajectory and the observed trajectory is approximately 5 m.

7 Conclusions and Future Work

This paper describes an emulator built around an autonomous model helicopter controller. The emulator accepts spacecraft thruster inputs (forces) and converts them into stick inputs for the model helicopter so that the helicopter can track trajectories designed for the spacecraft. To our knowledge this is a novel emulator design

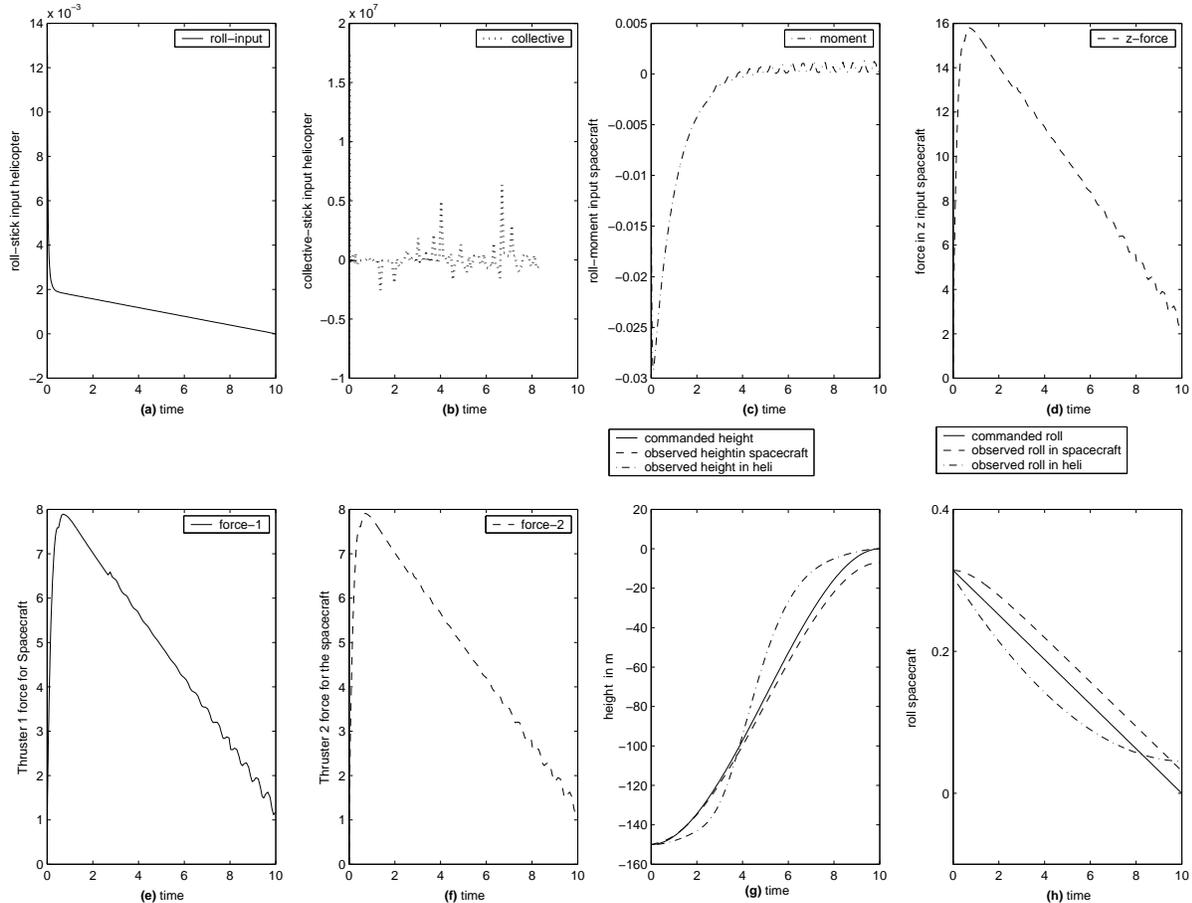


Figure 4: Landing emulation descending from a height of 150 m. Subfigure (a) and (b) show the cyclic pitch input and the collective input for tracking the trajectory given in (g) and (h) respectively. subfigure (e) and (f) shows the thruster inputs required by a spacecraft for tracking the same trajectory.

concept. We show simulation results which provide initial evidence that the model helicopter is able to track the trajectories specified by the spacecraft with reasonable accuracy. The results presented in this paper are preliminary and rely on a number of simplifying assumptions. The spacecraft model used here is a small perturbation model and hence cannot be used for tracking varying roll, pitch and yaw simultaneously. But for the class of problems that we are considering we do not consider this as a major problem since landing is essentially a 3-DOF problem with varying inputs in height, either x or y directions and roll or pitch input and the model presented here is capable of tracking small variations in all these four degrees of freedom.

In the future, we plan to validate our results on our model helicopter platform by identifying the model used here. We also plan to extend the controller so that we can track in 3D. We plan to explore the use of a neural network to train the transfer function so that we would be able to get better results. Finally we plan to test with realistic trajectories, based on the output of a vision-based hazard detection algorithm for landing.

Acknowledgments

This work is supported in part by NASA under JPL/Caltech contract 1231521 and by DARPA under grant DABT63-99-1-0015 as part of the Mobile Autonomous Robot Software (MARS) program.

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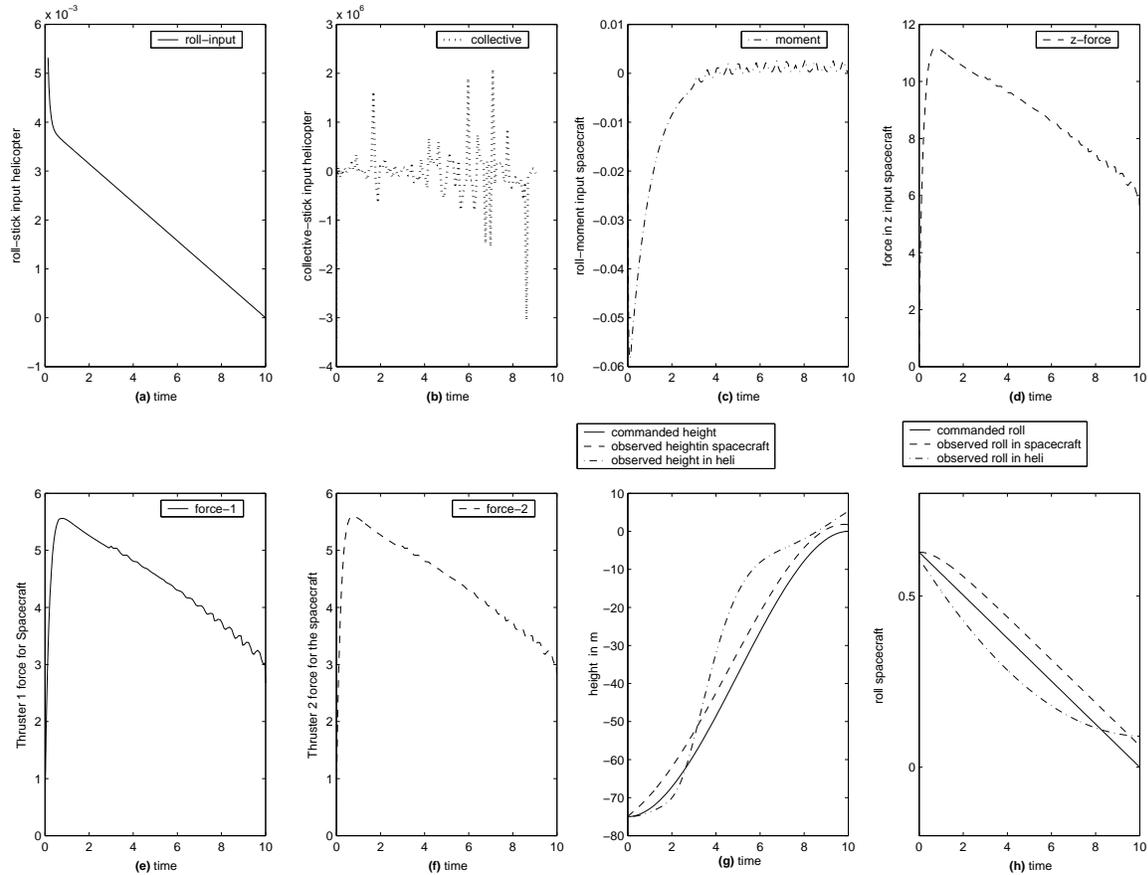


Figure 5: Landing emulation descending from a height of 75 m. Subfigure (a) and (b) show the cyclic pitch input and the collective input for tracking the trajectory given in (g) and (h) respectively. subfigure (e) and (f) shows the thruster inputs required by a spacecraft for tracking the same trajectory

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